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QUANTIFYING THE EFFECT OF TECHNOLOGY AND MANAGEMENT ON WHEAT YIELDS IN THE WESTERN GREAT PLAINS

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Abstract. *The relative influences of interannual climate variability, technological development, and management strategies on crop yields are difficult to separate. Assessment of climate impacts and of an agricultural system's ability to protect crops from weather-related yield changes are important questions receiving considerable attention in view of the potential for climate change. Statistical and ecological crop-climate studies have assumed that the combined effects of technology and management have produced linear or exponential yield increases in most crops in recent years.*

In this study, an empirical assessment of influences of management and technology on wheat yields in north-central Colorado was made using a control crop of unmanaged native shortgrass vegetation. A signal of climate variability was identified for the native grass, and was removed from the record of wheat yields, leaving departures termed the Management-Technology Index (MTI). The shape of the MTI curve was distinctly unlike the linear or exponential trend assumed in other models. The Index showed high variability from 1940 to 1963, but from 1963 to 1982 was characterized by step-functional increases. The step-functional behavior was interpreted to reflect the process of innovation diffusion.

Interannual variation in agricultural productivity results from a complex of factors, including weather, antecedent to and during the growing season, political decisions and market conditions, and changes in types and levels of management and technology. Despite progress in crop science, climate variability apparently remains the single largest influence on yield variability (Baier 1979; Biswas 1980; Warrick and Riebsame 1981). Warrick and Riebsame (1991) suggested that Dustbowl-era weather with the 1975 level of technology and management would reduce Great Plains wheat production, although the impact would be less than that of the 1930s.

Many scholars of climate impact assessment have sought to explain the influence of year-to-year changes in weather on crop production (Call and Hallsted 1915; Cole and Mathews 1940; Thompson 1962, 1969; Baier 1979; Biswas 1980). The distinction of the influence on crop yield variability of management and technology from that of climatic variability is complicated by the lack of detailed annual records for technological and managerial inputs. Trends of increasing yields are apparent in many studies of various crops and have been attributed to management and technological factors (Haigh 1977; Biswas 1980). Most researchers have assumed that the signal of climatic variability is represented by the departures of yearly yields from the simple trend of increasing yields, described as a linear, segmented, or exponential curve (Thompson 1962, 1969; Haining 1978; Biswas 1980). That assumption, however, has not been directly validated.

In this study, we approach the problem from a different direction than most workers. Our premise is that we can identify the influences of climatic variability in the biomass productivity records for a native, unmanaged vegetation that serves as an analog for the managed crop. We separate the signal of climatic variability from a record of a crop that has been subjected to managerial and technological innovations. The residual variance in crop yields, we argue, must be a record of nonclimatic influences, including management and technological factors. We are thus able to examine the validity of assuming a simple technological trend.

Results of our work contribute to an ongoing effort to monitor crop yields in response to changing natural and social environments. Michaels (1981, 1982) suggested that the link between climate and yield variability may be increasing as the lack of genetic diversity in new high-yield varieties "will reduce the range of climate to which they can respond favorably" (Michaels 1981:307). This possibility was also considered by Garcia et al. (1987:1,101), who stated "The increased variability of yields could either be a function of the heightened sensitivity of technology to weather, or to temporal increases in weather variability." Baker and Gersmehl (1991) showed that temporal trends of increasing productivity, identified at national levels, were not always identifiable in county soil report data.

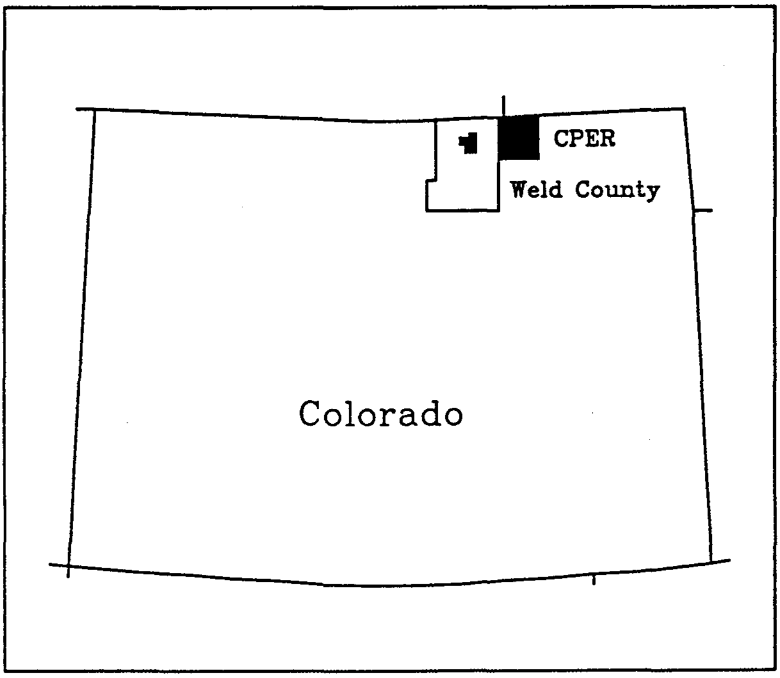

Figure 1: Location of study area: The Central Plains Experimental Range within Weld County, Colorado.

Ecology of Native Grass and of Wheat

The study site is the area on and around the Pawnee National Grassland in north-central Colorado (Fig. 1). The Central Plains Experimental Range (CPER) is a grassland ecosystem free from technological management, entirely within Weld County. Several crop-climate studies have been conducted at the site (Costello 1944; Bokhari 1978; Sala and Lauenroth 1982). In this semiarid environment, moisture is the predominant limiting factor in plant growth.

The large moisture variability inherent in semiarid regions and dryland crops' natural sensitivity to climatic influences combine to maximize direction and magnitude of response to climate change and variability (Graf 1982). In this study, we have assumed that on a large scale the climatic responses of native grasses and of wheat are sufficiently similar so that the modeled climatic response for grass is an analog for the wheat yield record.

Of course the analogy of grass and wheat is only approximate, with many points of difference. The relationship, however, is sufficiently close that we feel the technique of modeling the climate signal in one and transferring it to the other is valid for our test of the form of the management signal. Also, our use of an integrative climatic index (the Palmer Drought Severity Index) serves to downplay the importance of specific differences.

In a related study, on the influence of climate on both wheat and native grasses (Law 1985), both wheat and shortgrass had similar responses to climate, with the exception of the response to midsummer (June and July) weather. Both groups of plants relied on spring runoff from winter snows to the same extent, and both were inversely related to spring and early fall water availability. The inverse relation with spring precipitation may be due to the fact that most spring precipitation comes in the form of blizzards and near-blizzards (Jameson 1984) and is thus in reality a temperature response.

In a simulation study, Rosenzweig (1990) found that most stresses on Great Plains wheat are due to increases in temperature rather than decreases in precipitation. A clear positive relation existed between increased water availability and increased yield or biomass production. Biomass data measure whole plant response, whereas crop yield data measure the response of the reproductive portions of the plants. Timing and moisture stress may result in differential responses at different stages between grass and wheat. This is a study of statistical association rather than experimentation. The wheat-grass similarity is an critical assumption, and intraseasonal variations may be critical. However, statistical approaches focus on large-scale relationships, and, if such relationships exist, they must be considered in designing crop-climate studies. Our assumption is that despite these differences there is a broad similarity in response which is judged to be satisfactory for the purposes of this study.

Data

The study required data on agricultural crop productivity, on productivity of an analogous unmanaged vegetation, and on climatic variables critical to vegetative growth. The United States Department of Agriculture (USDA) has kept records on winter wheat production (bushels) and yield (bushels per acre) in the study area since at least 1919 (Colorado Department of Agriculture 1919-1982). Yield is a preferred measure, because it elimi-

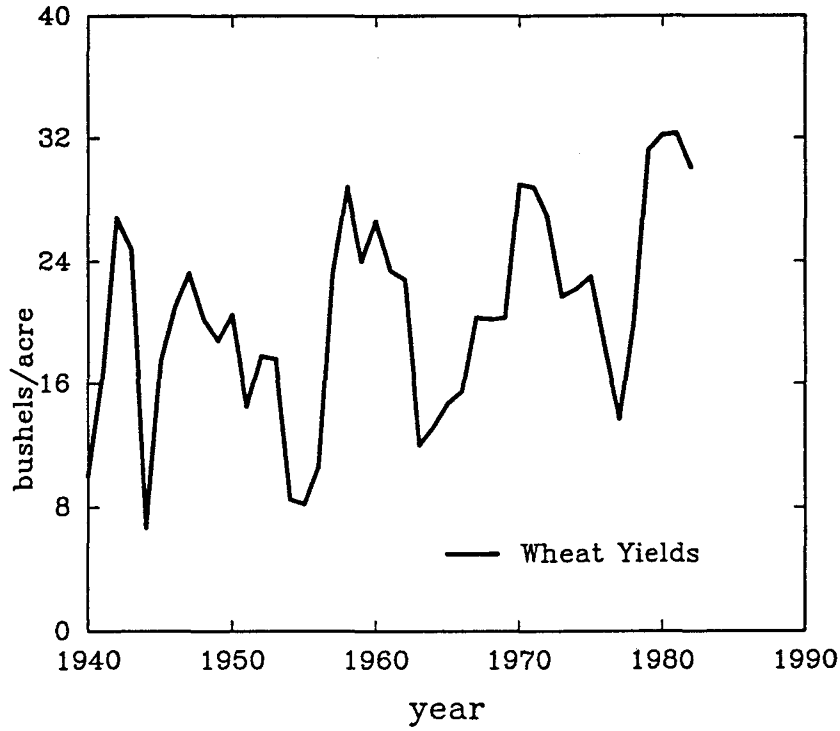

Figure 2: Dryland winter wheat yields for Weld County.

nates complications that might arise from changes in cropped acreage due to political, market, or other decisions. Yield per acre was calculated by dividing total production of the county by total number of acres cultivated with winter wheat. The time series of yields for Weld County shows an overall increasing trend, with low yields in 1944, the mid-1950s, the mid-1960s, and the late 1970s (Fig. 2). High yields occurred in the early 1940s, late 1950s, early 1960s, late 1960s, early 1970s, late 1970s, and early 1980s. The slope, about 2.5 bushels per decade, accounted for less than one-quarter of the variance in yields but was significant at the 0.05 probability level.

The control vegetation data were biomass measurements, in air-dried pounds per acre, of native shortgrasses, principally blue grama [*Bouteloua*

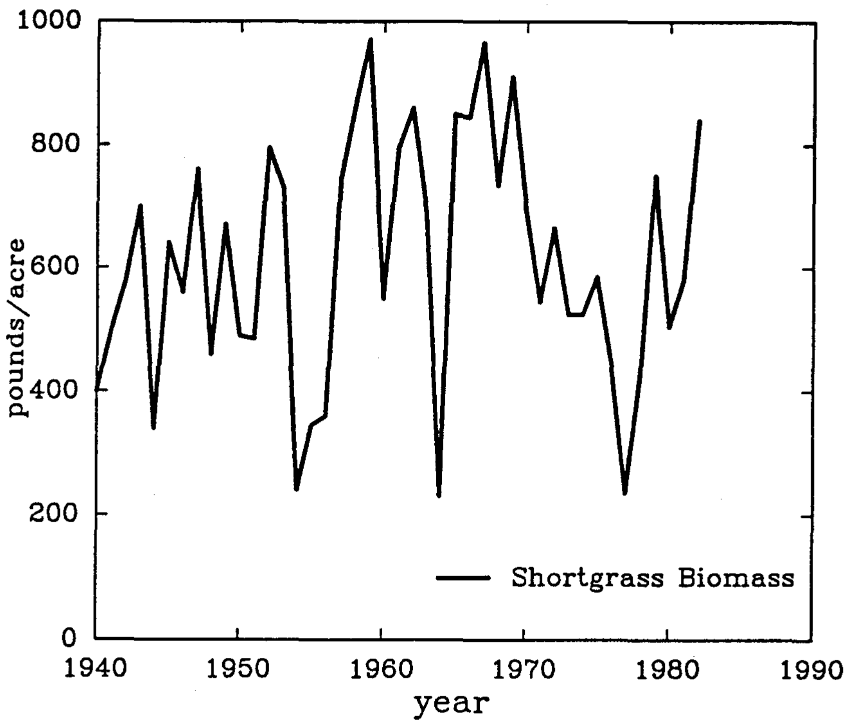

Figure 3: Shortgrass Biomass Production, CPER, Weld County.

gracilis (H. B. K.) Lag. ex Griffiths] and buffalo grass [*Buchloe dactyloides* (Nutt.) Engelm.] (Redetzke and Paur 1973) (Fig. 3). Observations were made by the Agricultural Research Service of the United States Department of Agriculture (ARS-USDA) at the CPER within the Pawnee National Grassland (Shoop 1984).

Data quality from 1940 to 1953 was poor due to crude field notes and nonstandard estimation techniques. Data from 1953 to 1960 were based on better estimation methods and thus were more reliable. After 1960, standardized collection methods and recording were implemented, greatly improving data reliability. The time series of shortgrass biomass production shows no overall trend. Productivity was low in the mid-1950s, early 1960s, and late

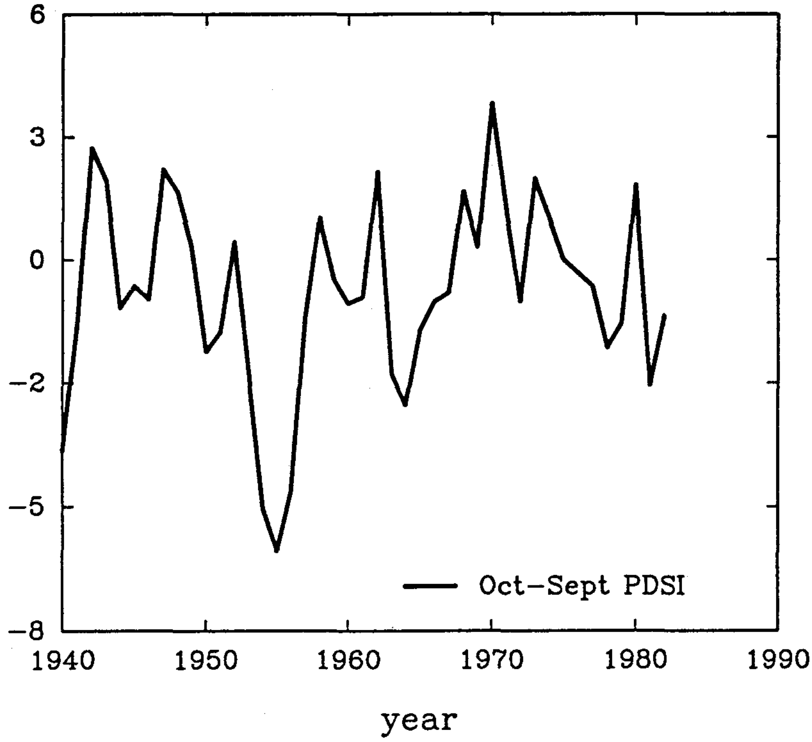

Figure 4: Mean of the October to September PDSI, Platte River Drainage Basin.

1970s. High productivity occurred in the late 1950s and late 1960s to early 1970s.

The climatic parameter used was the Palmer Drought Severity Index (PDSI) for the Platte River Drainage Basin climatic division of Colorado, which encompasses both Weld County and the Pawnee National Grassland (Fig. 4). PDSI quantifies departures from "normal" in local area water budgets (Palmer 1965; Karl 1983), and thus was judged a suitable measure of the major stress experienced by the vegetation. Considerable spatial variability exists in precipitation in semiarid regions, especially in summer when mesoscale convective activity is the primary mechanism (Nicks and Hartman 1966). Use of PDSI for the climatic division filters out much of the small-scale variability and focuses on interannual anomalies of a spatial scale commensurate with the areal biomass and crop data. The PDSI time series shows no secular trend. Droughts occurred in the mid-1950s and the early 1960s. Wet periods occurred in the early 1940s, the late 1940s, and the late 1960s.

Methods

Since the wheat and shortgrass productivities were measured in incommensurate units, the two series were transformed into series of departures. Normalized values (z-scores) were calculated by subtracting the average and dividing by the standard deviation for each data set, using the common period of record, 1940-1982.

Some carryover effect of climate from the previous year on the current year's grain productivity was expected, due to recharge or depletion of soil moisture. Therefore, shortgrass production series was smoothed by application of a weighted moving average operator. Weights were chosen to represent the relative influence of the current and preceding years' climate, and were determined as follows. The PDSI was averaged across the 12-month period from October to September, since the shortgrass was usually clipped in September. The average PDSI in the preceding year was used in addition to the current year's value since the soil moisture budget depends somewhat on antecedent conditions. Relative importance of the preceding and current year was estimated as the ratio of the appropriate individual Pearson product-moment correlation coefficient to the multiple correlation coefficient. In this case, the first year's correlation of shortgrass biomass with PDSI values was 0.47 and the preceding year's correlation 0.18. The multiple correlation coefficient was 0.65. Dividing 0.47 by 0.65 resulted in a first year weighting of 0.72, and dividing 0.18 by 0.65 resulted in a weight of 0.28 for the preceding year. These proportions were used to produce weighted moving averages of the shortgrass z-scores.

The climate signal in the smoothed standardized series of shortgrass production was identified by polynomial least-squares regression. The polynomial regression technique was chosen to fit a curve that described the high and medium frequency fluctuations in productivity of the vegetation attributable to interannual climate variability. It must be emphasized that the aim was to create merely a descriptive model, not a diagnostic one. A relatively high-order fit was justified, as the climate signal is actually quite complicated, and dependent upon which the degree and duration of the limiting

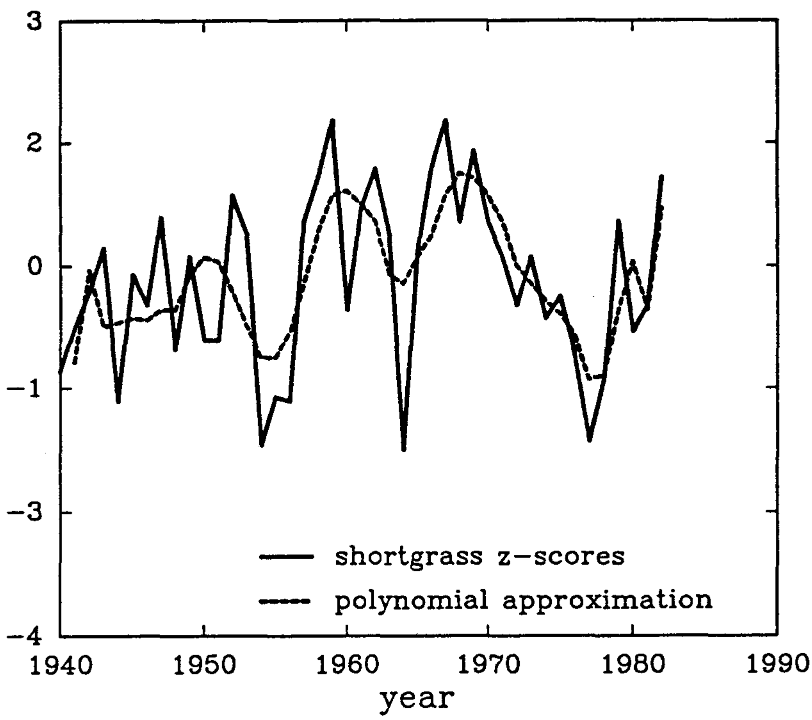

Figure 5: Shortgrass biomass z-scores and the polynomial approximation made using the moving average weights of 0.72 and 0.28.

factors. That is, the productivity data represent a completely integrated signal. The fifteenth-degree polynomial used was the maximum degree allowed by the statistical program (Dixon 1983), and accounted for the most variation of any of the polynomials calculated.

The polynomial expression of the standardized scores was subtracted from the standardized wheat time series. The residuals, we contend, reflect differences in impacts of weather events or differences in management and technology. By focusing on the trend of these residuals, termed the Management-Technology Index (MTI), we determined whether the trend was linear or curvilinear.

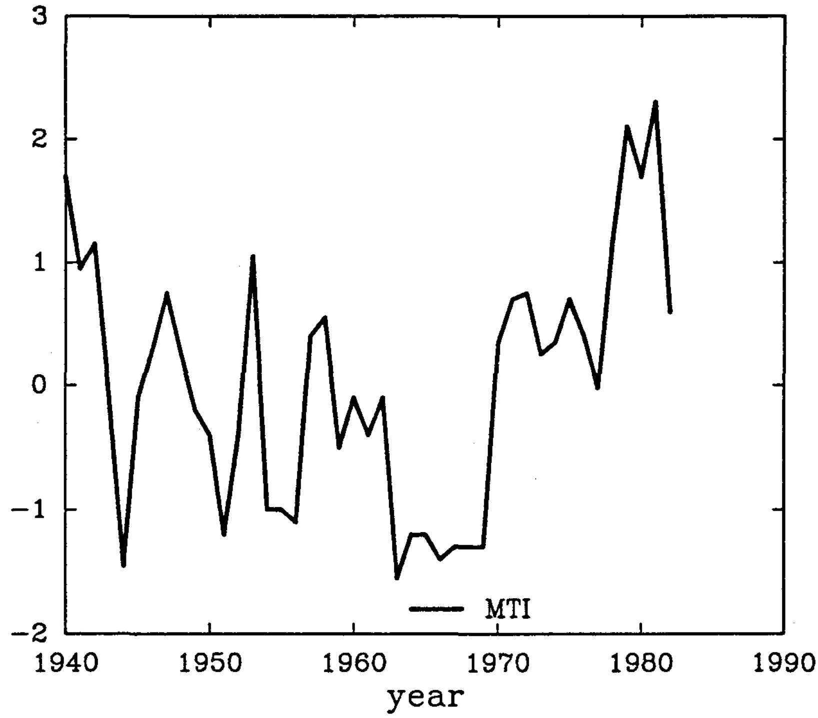

Figure 6: Management-Technology Index with moving average weights of 0.72 and 0.28.

Results

The fifteenth-degree polynomial fit to the biomass z-scores explained 59% of the variance (Fig. 5). The fit appeared to be better in the later years, after about 1963, than in the early years. The uncertain quality and reliability of the biomass data discussed above may be responsible for this behavior. Independent analyses were made with abbreviated data sets as checks. The fits of polynomial curves to the abbreviated series were better, with 80% explained variance for the 1953-1982 data set, and 96% explained variance for the 1960-1982 data set. However, these large explained variances may be due to overfitting the model (the use of a high-degree polynomial to describe a short time series). In both abbreviated data sets, the fit during the latter years was best.

The MTI showed high variability from 1942 to 1963 (Fig. 6). After 1963, however, the series exhibited apparent step-functional behavior. A period of nearly constant values with very little variability occurred from 1963 to 1969. Values of MTI increased abruptly in 1970, then leveled off in another period of stability and reduced variability until 1977. Another large increase was observed in 1978, beginning four years of the highest values in the record. The year 1982 saw a drop in the MTI, but we have not discovered an apparent reason for this reversion.

The stable periods each have far less variability than the pre-1963 values, and are separated by large, sudden increases in the MTI. Mean MTI for each of the episodes are significantly different from the others. Comparison of MTI with wheat yields suggests that inputs of management and technology and resultant yields were rising concomitantly, but the wheat yields were still highly variable.

Conclusions

The MTI series can be subjectively divided into two distinct segments. The first segment, that before 1963, was highly variable with no apparent trend or episodic behavior. This portion of the series was made up of data which was somewhat suspect, possibly accounting for the obvious change in character after 1963. The second part, post-1963, consists of three episodes separated by distinct steps: 1963-1969, 1970-1977, and 1979-1982.

The step-functional nature of the post-1963 record corresponds to an expected diffusion pattern of technological and management innovations (Hagerstrand 1967; Warrick and Riebsame 1981). An innovation is first brought to the attention of a few farmers, who "field test" the new product or technique. If successful, the improvement is then adopted by more farmers. Since information on technology and management flows freely within the agricultural community (Perrin and Winkelman 1976; Butler 1980; Thompson 1984), once "field tested" and found useful the improvement quickly becomes applied over a large area (Hagerstrand 1967; Thompson 1984). The diffusion process over time is thus described by a logistical curve, which at certain areal and/or temporal scales may appear to be step-functional. In this study, there appear to have been two steps since the early 1960s.

We have not been able to identify particular innovations responsible for those steps within the study area; this would require examination of independent data on agricultural technology. However, the quick spread of new high yield-drought resistant hybrids and of fertilizers may be partially responsible, especially for the 1963 step (Echols 1984). The economic conditions leading to large corporate farms may also improve management, but broader economic conditions (expressed as national wheat prices) appear unrelated to the MTI pattern (Law 1985).

Our results are contrary to the simple linear or exponential curves for technological influence assumed in many crop-climate models (Thompson 1962, 1969; Haining 1978; Biswas 1980). For a large region such as the Great Plains or the nation, the net effect of numerous subregional diffusion processes each with different temporal and spatial characteristics might appear to be that described by the simple curves. However, much detail is lost; at smaller scales the step-functional behavior probably dominates.

Researchers have found it difficult to assess the full range of influences affecting plant growth in both statistical and ecological models. In statistical models simple assumptions are needed to identify trends due to management and technology. In ecological models the management and technological factors (i.e., fertilizer, genetics, irrigation) are usually analyzed individually, demanding detailed data, and making analysis of the synergistic effects very difficult. The method of assessing the management/technological influences employed here provides another perspective. Thus, this methodology may be applied to any case where crop and unmanaged comparable native crops have coexisted for a sufficient length of time, and may provide additional insight into statistical crop-climate relationships.

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